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INTERIM REPORT NO. 5
RESEARCH AND DEVELOPMENT
OF
CACHE MARKER SYSTEM

PHASE II: DEVELOPMENT OF ENGINEERING
PROTOTYPE

Covering the Period

15 August 1953 to 15 October 1953

Contract No.

16 November 1953

This document contains information affecting the national defense of the United States within the meaning of the Espionage Laws, Title 18, U.S.C., Sections 793 and 794. The transmission or the revelation of its contents in any manner to an unauthorized person is prohibited by law.

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ABSTRACT

The construction of the portable Q-Meter detection system has been completed. Tests in the laboratory indicate a maximum range of about 8 feet between detector and transponder. Using an aural indication, modifications made to improve the sensitivity of the detector have resulted in no increase in range. An increase in range of about $2\frac{1}{2}$ feet was obtained with the use of a meter indication. This resulted in a less stable circuit.

Transponders incased in a glass fibre reinforced plastic shell have been tested. The results indicate that they can be made watertight with proper care. The detectability of the transponder is not altered by being encased in the plastic shell. Further efforts to find a suitable material for potting the transponders have been unsuccessful. Further work in this direction was discontinued.

A coil winder to wind coils of the design used for the transponder was designed and constructed in order to demonstrate that the transponder coils can be wound by machine.

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I. DETECTION SYSTEM

1. Construction Details of Detector

The construction of the detector according to the circuit given in Interim Report Number 4 was completed during this period. The positions of the components which make up the detector and its construction details are given in the series of photographs which appear on page numbers 3, 4, 5, 7 and 8.

Figures 1, 2, and 3 show bottom, side, and top views respectively of the detector in its folded position. The band switch and main tuning control can be seen in Figure 1. In Figure 2 the amplitude control can be seen in the lower right corner of the metal case which contains the circuits of the detector and the battery power supply. One of the switches which is used to turn on the detector can be seen at the center of this case. Figure 3 shows the Faraday shield of the detector coil. The lead from the center of the shield to one edge of the case grounds the shield to the case. The two leads on the left side connect the detector coil to the circuits within the case. In Figure 4, the detector is shown in its open, or operating, position. The coil is supported in this position by means of the cloth tape in the center and the braces on either side. On the side of the case may be seen four rows of buttons which when removed allow access to the padders and trimmers for adjusting the oscillator and the detector circuits. Two trimmers and two padders are used for each frequency band. Figure 5 shows the detector taken apart. The top and bottom plates are removable to give complete access to the electric circuits without removal of the detector from its case. With the top plate removed the batteries can be replaced as well as the tubes. The removal

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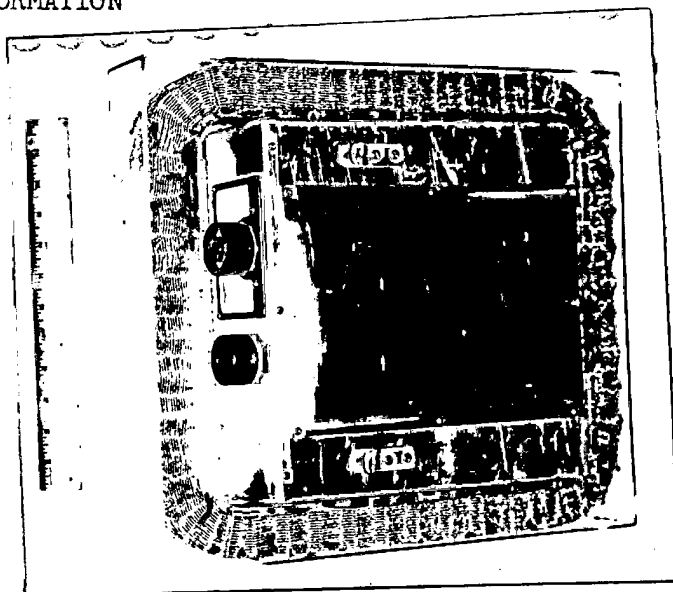


Figure 1.
Bottom View of Detector

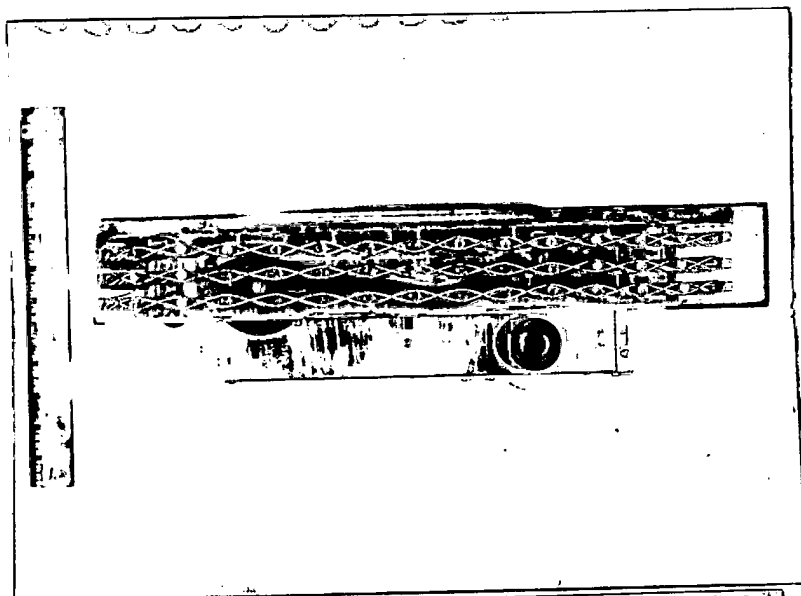


Figure 2.
Side View of Detector

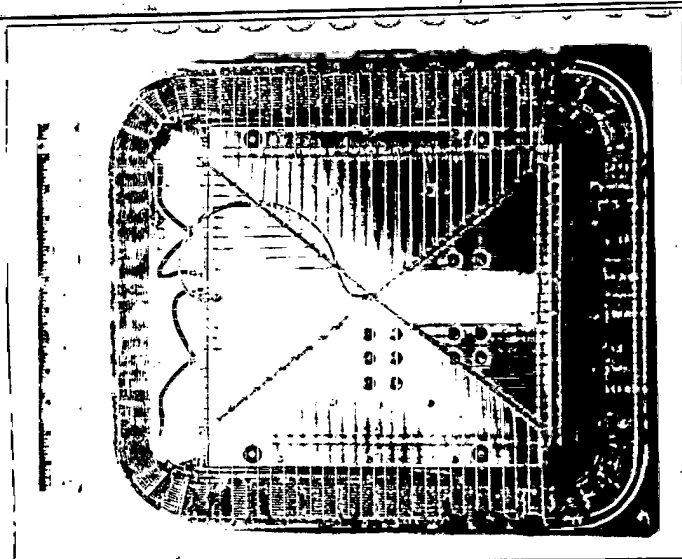


Figure 3.
Top View of Detector

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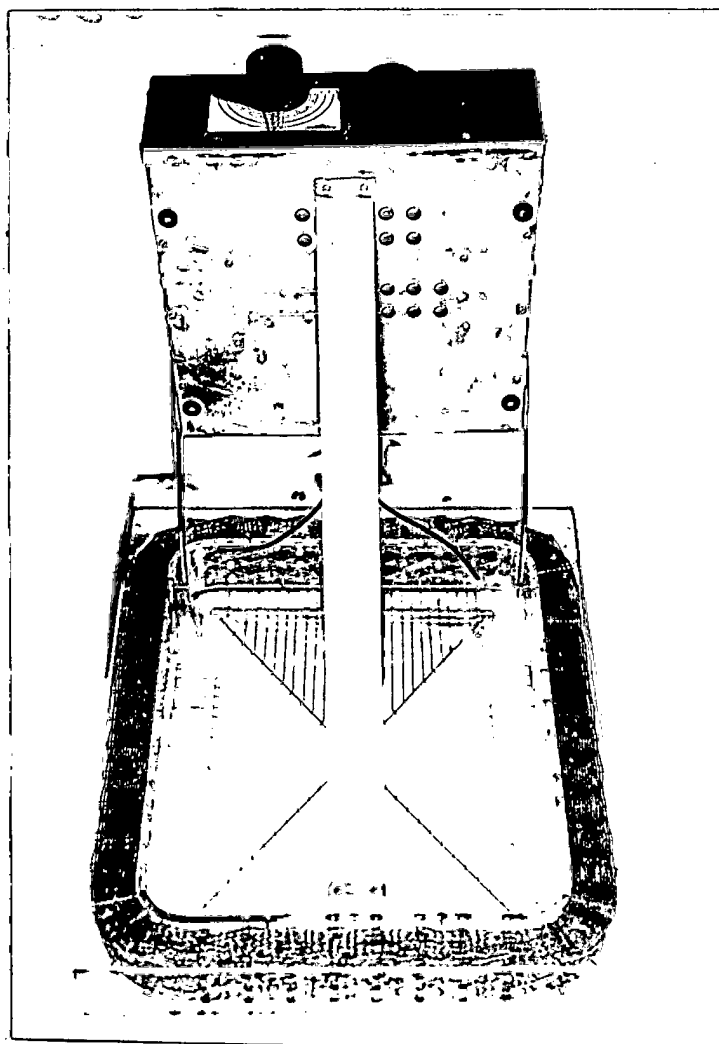


Figure 4. Detector in Operating Position

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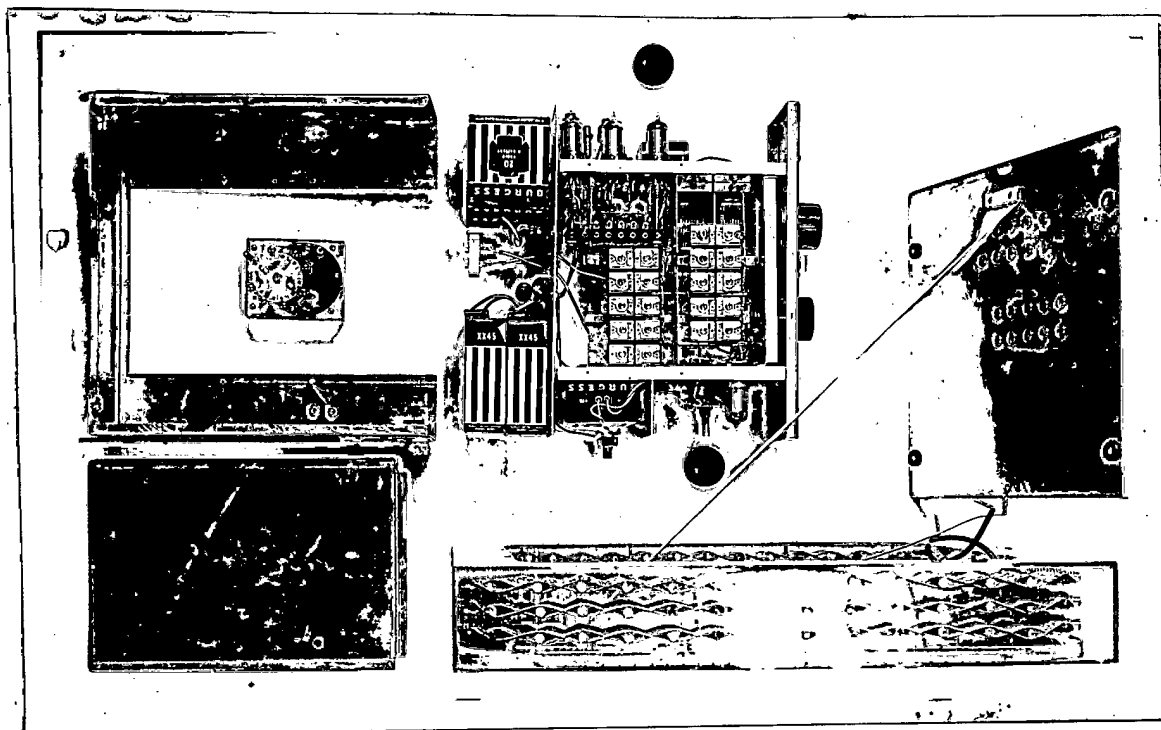


Figure 5. Detector Disassembled

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of the tubes without removing the detector from its case is made possible by means of large plug-in buttons which coincide with the position of the tubes. Figure 6 is an enlarged view of the detector removed from its case. The oscillator and its frequency determining circuits occupy the upper compartment and the receiver and its frequency determining circuits occupy the lower compartment. The oscillator tube and circuit are in the upper right hand corner. The lower right hand corner contains the receiver amplifier. Most of the space is occupied by the frequency determining circuits which are needed to give the degree of flexibility which is required. The power supply consists of two $67\frac{1}{2}$ volt batteries which supply B plus to the oscillator and receiver and the bias required for the input stage of the receiver. These batteries occupy the lower right hand position. Three filament batteries are used. The $1\frac{1}{2}$ volt battery on the right side supplies the filament voltage for the Hartley type oscillator. The two filament batteries for the receiver occupy the lower left hand position. Figure 7 shows the rotating capacitor. Figures 8 and 9 show two views of the rotating capacitors and clock motor.

2. Operation of the Detector

The completion of the construction of the detector was followed by careful checking of its operation. One of the first things that was noticed was a background noise which sounded like 60 cycle pickup. This noise was finally attributed to interaction between the receiver and transmitter circuit whose plate voltages are supplied by the same batteries. A decoupling network was placed in the plate circuit of the oscillator which removed this condition. Tests to determine the ranges at which transponders could be detected gave distances of 8 to 10 feet depending on the adjustment of the amplitude and fine tuning controls.

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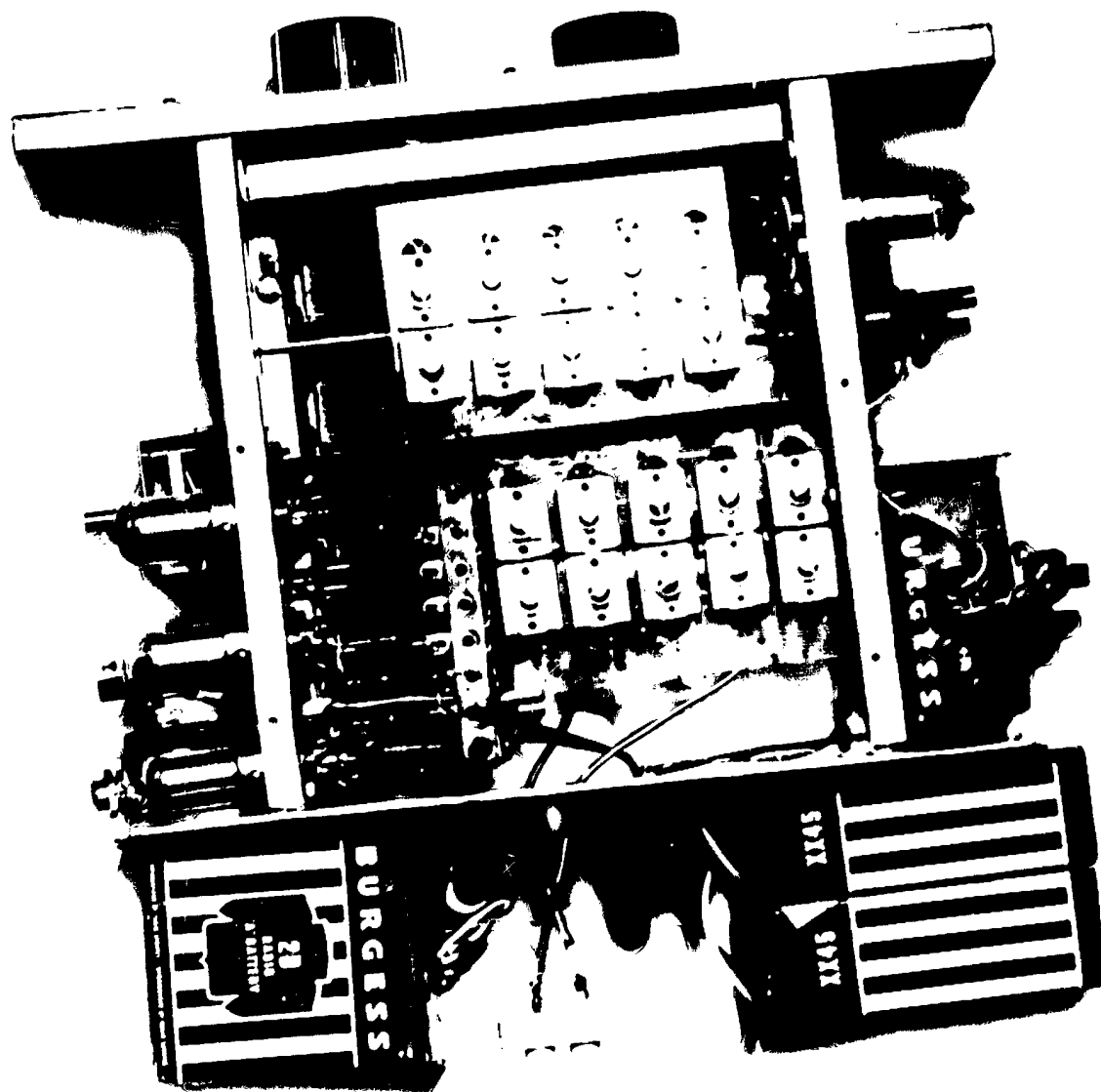


Figure 6. View of Detector Circuit.

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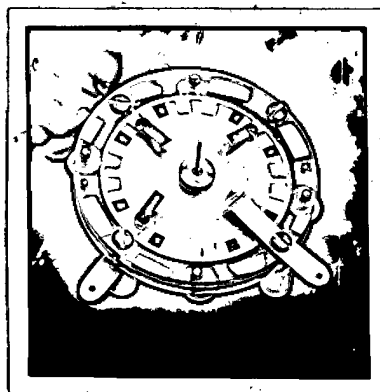


Figure 7. The Rotating Capacitor

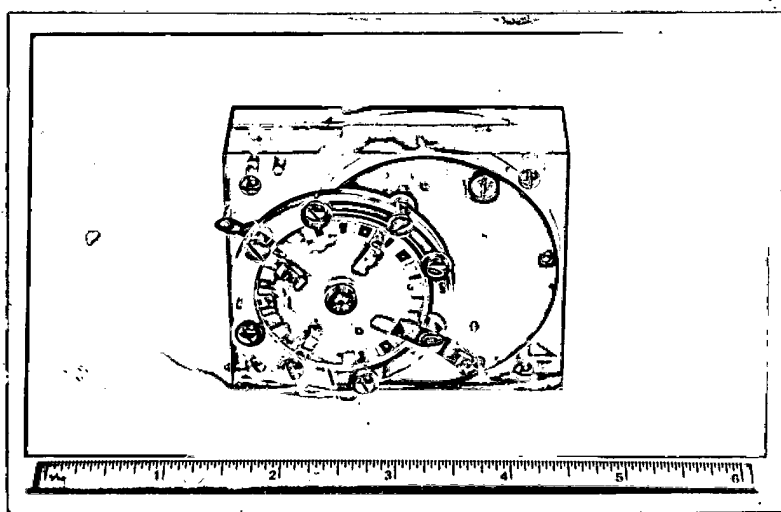


Figure 8. Rotating Capacitor Mounted
on Case of Clock Motor

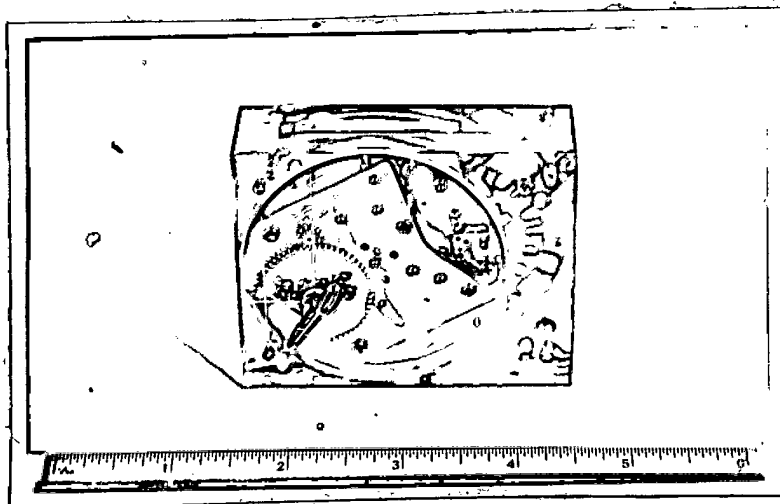


Figure 9. View of Clock Case Showing
Clock Mechanism

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It was observed that large metal objects (such as a tool box) placed within six inches of the transponder reduced the range at which the transponder was still detectable. This effect seemed to be more pronounced when the metal object was behind the transponder than when in front of the transponder. This means that a cache consisting of a large metal object will have to be placed a foot or more below the transponder. Tests should be made to determine what the distance between the transponder and the cache should be in order not to seriously reduce the range of detectability.

Modulation of the oscillator instead of varying the resonant frequency of the series tuned receiver circuit was tried. It was found that this resulted in a "cleaner" signal. Frequency modulation of the oscillator has the additional advantage of not requiring a high Q rotating capacitor. The Q of the oscillator circuit is lower than that of the receiver circuit and its operation is not affected by the addition of a relatively low Q capacitor. This permits the case of the rotating capacitor to be made of a plastic which has better mechanical properties. Although frequency modulation of the oscillator is used to accomplish the same thing as modulation of the resonant frequency of the receiver circuit, the mathematics describing the two actions are considerably different. Details are given in the Appendix.

The tracking errors on some of the bands were larger than could be compensated for by the present rotating capacitor. A new rotating capacitor is being built which will have twice the capacity range and half the rate in capacity variations. This is being accomplished by reducing the number of teeth by half and making them twice as big in area. There are theoretical results indicating that a reduction in the rate of capacity variations will result in improved operation in tracking.

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An increase in the range of the detector was accomplished by rectifying and filtering the audio signal and displaying the result on a d.c. vacuum tube voltmeter. This resulted in a gain in range of about $2\frac{1}{2}$ feet. However, the variations in magnitude of the audio signal, to which the ear is not sensitive, caused the meter to move erratically thus requiring a filter with a one second time constant. This additional range was obtained with a sacrifice in operational utility. The rate at which the main tuning control could be rotated was limited by the time constant of the filter and the response of the meter. In addition an aural indication is considered to be considerably more desirable than a meter indication.

Observations of the wave forms on the grid of the first amplifier stage of the receiver circuit indicated an extremely small voltage when the amplitude control was adjusted for a comfortable, audible level at the earphones. It appeared that improvement in sensitivity could be obtained by raising the magnitude of the signal that could be comfortably handled at the earphones. This was accomplished by introducing positive bias at the cathode of the second amplifier stage of the receiver thus causing clipping of part of the signal. This amounts to having a second "window" in the receiver circuit. These modifications resulted in no improvement of the sensitivity of the detector. Using the input stage of the receiver circuit as a "window" voltage amplifier was tried to determine whether additional gain obtained in this way would result in increased sensitivity. This resulted in an unstable circuit.

3. Position of the Detector Coil

Interim Report Number 4 mentioned two possible configurations of the detector coil with respect to the operator. The most desirable configuration would be one in which the operator wears the detector coil as a belt.

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The problem in accomplishing this in practice is that of controlling the distributed capacity between detector coil and operator. If the changes are greater than that which can be compensated for by the rotating capacitor, detuning results. This results in a null in the aural indication which could be misinterpreted as the presence of a transponder. Effective shielding which reduces the variation of capacity to a point where the rotating capacitor can compensate for these variations also reduces the Q of the detector coil by a factor of ten or more. The sensitivity of the detector is reduced by the same factor. No further work will be done on attempting to place the operator inside the detector coil. The configuration of the detector coil that is presently being considered is shown in Figure 10.

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Figure 10. The Detector in Operating Position
with Operator

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II. TRANSPONDERS

1. Shell-structure

The design of the shells that are to be used for the packaging of the transponders, which was presented in the last Interim Report, required only one set of matched metal molds for production. However, because of the difficulty in joining a pair of shells of this design together and obtaining a watertight joint, the design has been changed. The two half-shells which make a packaging unit are slightly different in size allowing one to fit inside the other. This does away with the flange on the inside and the sealing band used on the outside. The joints are sealed with an epoxy resin. A small hole drilled in one of the half-shells allows the air to escape freely rather than forcing its way through the joints thus leaving places in the joint through which water can later seep through. This hole can also be used when checking to see that the joints are really watertight. This can be accomplished by applying compressed air to the transponder submerged in water and observing whether or not air bubbles appear.

The question of whether this structure will remain watertight after five to ten years is one which is difficult to answer. As an extra insurance against the possibility of moisture getting at the coil we will dip the coils in ceres wax thus further protecting them against the leakage or seepage.

In the initial work with Chance Associates on the fabrication of the glass fibre reinforced plastic shells it was decided that three different types of structures would be tried. All three methods involved telescoping half-shells. The first method consisted of thin shells, about 1/32 of an inch thick, in which the transponder is placed and then wrapping the

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assembly with glass fiber tape that has been saturated with polyester resin in a manner similar to the way new automobile tires are wrapped (See Figure 11). The second method consisted of thick telescoping shells about 1/16 of an inch in thickness bonded together with an epoxy resin (See Figure 12). The third method consisted of a thin and a thick shell with the shell which fits on the outside being the thick one. A third shell is then formed by hand laying up of glass fiber mat and resin on that part of the structure which is thin walled.

Laboratory tests have indicated that the materials used for these structures do not alter the detectability of the transponders. The transponders have been submerged in saltwater for several days at a time to determine whether or not they are watertight. The transponder of the construction first mentioned was decided to be unsatisfactory. Whether or not it will remain watertight depends on the quality of the many joints formed in wrapping and of the three methods it is the most difficult to make. No more consideration will be given to this type of structure. The other two structures have both proven to be watertight. The ten transponders that are being packaged for us by Chance Associates will be made by both of these methods.

2. Coils

The coils for the ten transponders were made by hand using plexiglass for the coil forms and Litz wire made of 24 strands of number 30 wire. The coil form and the finished coil are shown in Figures 13 and 14. Data were taken of the mechanical and electrical properties of the coils to obtain some measure of the reproducibility of these properties in manufacture. The variation in physical dimensions was larger than would be expected in manufacture. The coil forms in production would be made by injection

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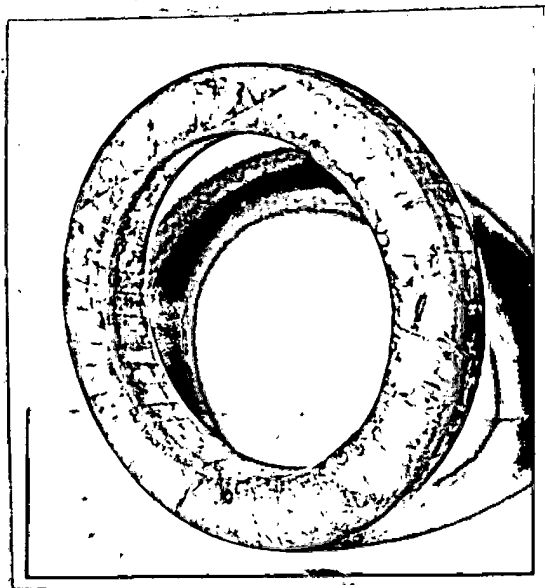


Figure.11. Transponder Encased in Thin
Shell and Wrapped with Tape

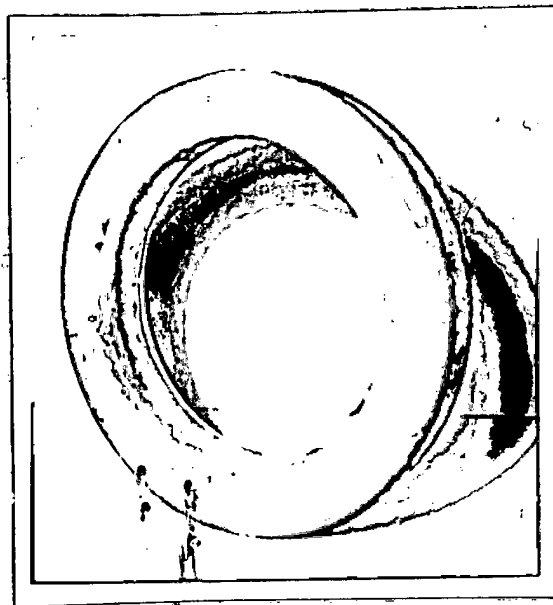


Figure 12. Transponder Encased in Heavy
Telescoping Half-shells

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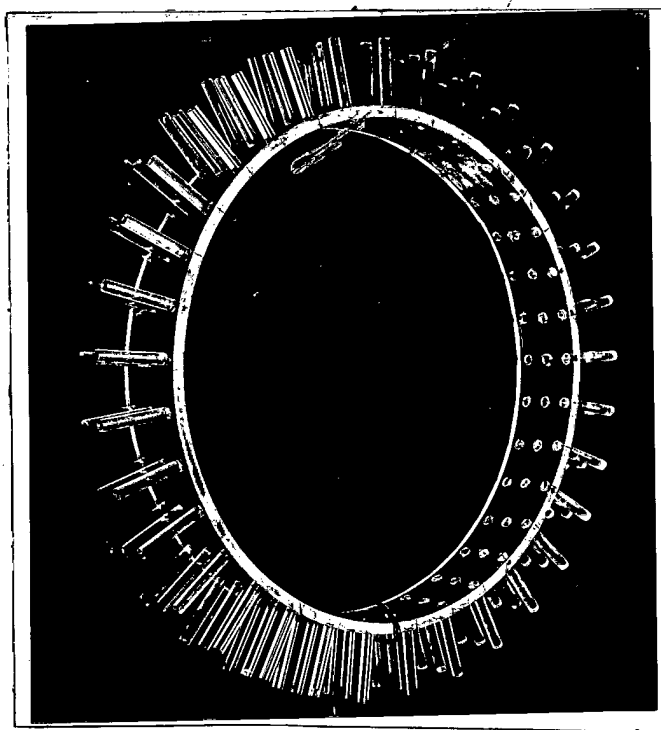


Figure 13. Coil Form

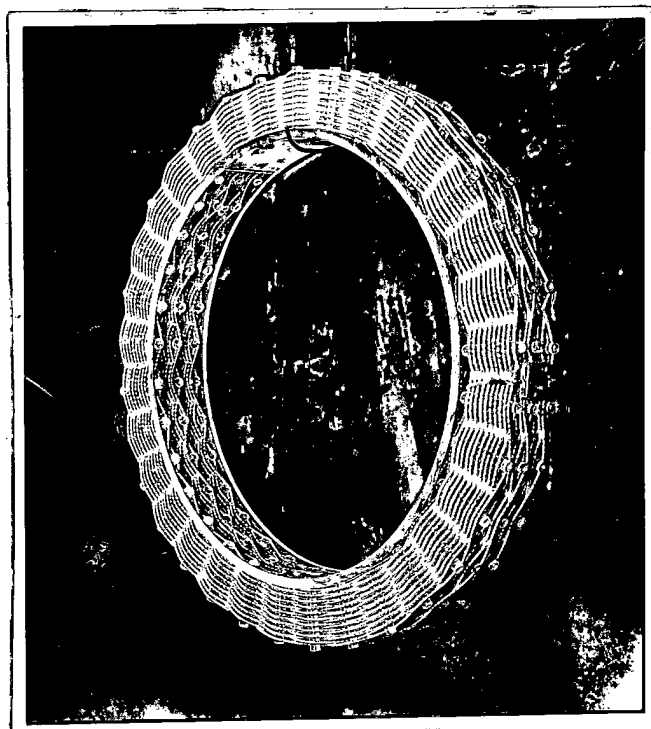


Figure 14. Transponder Ready for Packaging

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molding where the tolerances can be kept to within 1/100 of an inch. For the ten coils the inside diameter varied from $10^{19}/32$ inches to $10^3/4$ inches. The outside diameter varied from $14\frac{1}{4}$ inches to $14\frac{5}{16}$ inches. For each coil the following electrical measurements were made: the D.C. resistance, the Q at 60, 80, 100, 110, and 140 KC., and the capacity needed to tune the coils to 100 KC. As a measure of the reproducibility of these quantities the standard deviations were computed. The results are as follows:

	Mean Value	Standard Deviation
D. C. resistance.	1.052 Ohms	0.025
Q at 60 KC	323.8	4.76
Q at 80 KC	352.5	14.13
Q at 100 KC	365.4	3.98
Q at 110 KC	363.6	2.62
Q at 140 KC	345.2	1.70
Capacity to tune to 100 KC	1449.8 mmf	4.94 mmf

If a normal distribution is assumed, the standard deviations give the most probable plus and minus limits for these quantities. The spread in values obtained is surprisingly small with the exception of the value obtained for the Q at 80 KC.

The probable contribution to the spread in frequency due to deviation in coil inductance for transponders supposedly tuned to the same frequency is computed from

$$\Delta f = -(\Delta C/2C)f$$

giving a value of 172 cycles per second for 4.94 mmf at 100 KC. This information in conjunction with data on the tolerances of the tuning capacitors used and the capacity affects of the earth and transponder case will determine how narrow the frequency bands can be made.

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During this period a meeting was held with [REDACTED]

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[REDACTED] to discuss the problem of potting the transponders.

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There are only a few plastics that can be used for this purpose because of the requirements for low dielectric constant and low power factor. The best materials in order of increasing dielectric constant and increasing power factor are polystyrene, tetrafluoroethylene, polyethylene and hard rubber. The dielectric constant for these materials varies from 2.6 to 3.0 and the power factor varies from 0.0001 to 0.005. Of these materials polystyrene is the only one which does not have the necessary mechanical properties. However, there are difficulties in handling the latter three materials. Tetrafluoroethylene has excellent mechanical properties but it is extremely difficult to handle and requires high temperatures in forming. In addition, it is expensive compared with the other materials. The same requirement of high temperature in forming is inherent with the use of hard rubber. Polyethylene which is a thermoplastic material melts between 110° and 150°C. It requires the lowest forming temperature with the exception of polystyrene. It is also a relatively low cost material and is therefore highly desirable.

Experiments were performed to determine the proper techniques for handling polyethylene as a casting material. One of the manufacturers of polyethylene, the Union Carbide and Carbon Company, has informed us that this material has never been used for casting but rather is used in injection molding processes. The difficulty that is encountered in trying to cast this material is primarily due to the large shrinkage which occurs when the material goes from a liquid to a solid state. It has an extremely

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high coefficient of expansion and upon cooling without the presence of external pressure forms cavities or cracks. In addition, the temperature at which this material melts is higher than that which is used for the coil form, namely a styrene or acrylic plastic. This would cause softening of the pegs of the coil form and distortion.

The investigations we have made for finding a suitable material for the potting of transponders have been unsuccessful. To the best of our knowledge there is no potting material which will satisfy the requirements of excellent electrical and mechanical properties and low cost.

4. Coil Winder

During this period a coil winder was designed and constructed. (See Figures 15 and 16.) None of the commercial coil winding machines that we are acquainted with will wind the coils of the design used for transponders. A machine was built to determine the feasibility of machine winding such coils.

The coil winder consists of a disc on which the coil form is placed, and a wire shuttle which moves back and forth as the coil form is rotated. The wire shuttle is actuated by two solenoids which are alternately energized as the coil form is rotated through the distance between pegs. The disc on which the coil form is placed has pegs projecting out the side which are equal in number to the number of pegs on the coil form. These pegs actuate a micro switch supplying an electrical pulse to a stepping relay which alternates its position every time it receives a pulse. A pair of contacts on the stepping relay energizes a relay which completes the circuit for one of the solenoids in the energized position and the other solenoid in the de-energized position.

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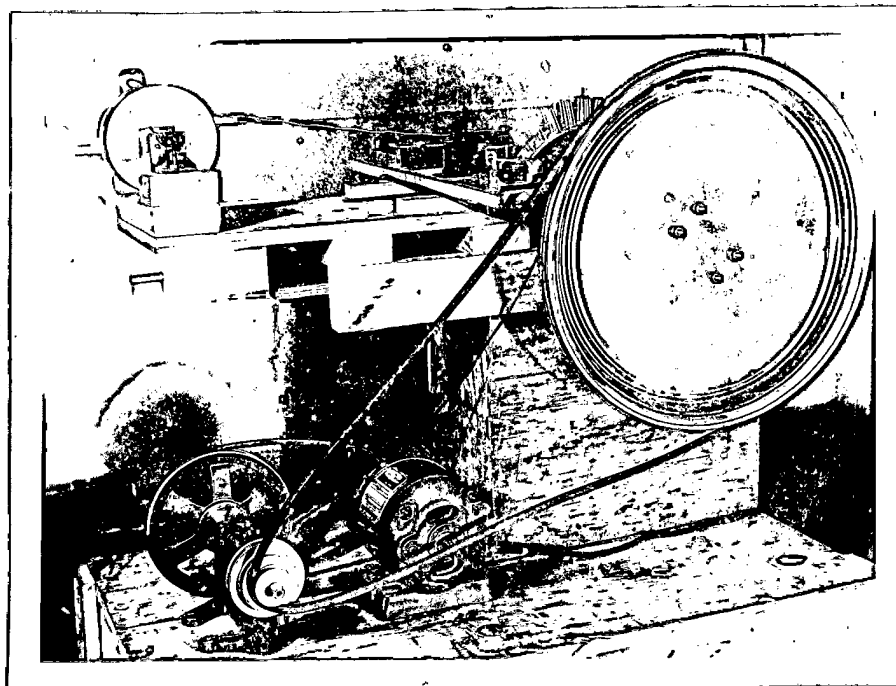


Figure 15. The Coil Winder

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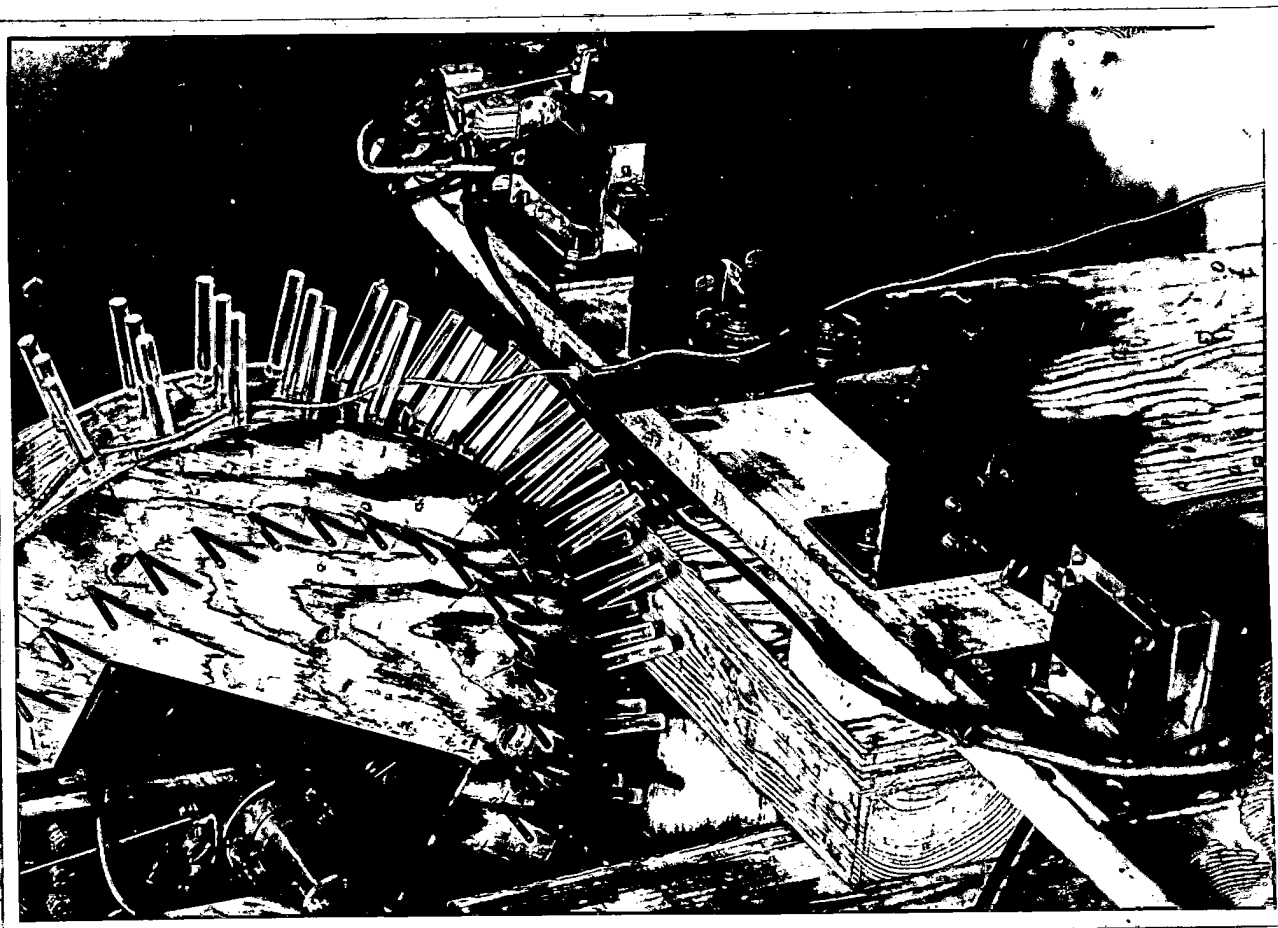


Figure.16. View of Coil Winder Showing Solenoid
Actuated Wire Shuttle and Controlling
Mechanism.

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The coil winder was tested and the design proved to be satisfactory.
No further work will be performed toward improvement.

Program for the Next Interval

1. Field tests of the detection system will be performed.
2. Construction of the prototype model of the detector reflecting the results of the field tests will be initiated.
3. Experiments will be performed to determine the effects of environment on the frequency and range of the transponder.

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APPENDIX: Two Systems of Modulation which Compensate for Tracking Error.

There are two methods of modulation that have been used for compensating for the tracking error which is the result of differences between the operating frequency of the oscillator and the resonant frequency of the series tuned circuit of the receiver. In the first method, the resonant frequency of the receiver circuit is continuously varied by means of a rotating capacitor. The maximum and minimum values of frequency that result are made sufficient to exceed the tracking error frequency differences. Thus, there is always a position of the rotating capacitor for which the frequency of the oscillator and the frequency of the receiver are the same. In the second method, the oscillator is frequency modulated by the rotating capacitor. The frequency deviation is made larger than the largest frequency difference that occurs. Thus, there is always a time during the modulation cycle when the frequency of the oscillator and the frequency of the receiver are the same. It appears that the two systems are the same but a careful examination indicates that this not true.

The first method of modulation (where the resonant frequency of the receiver is varied) is indicated by Figure 17.

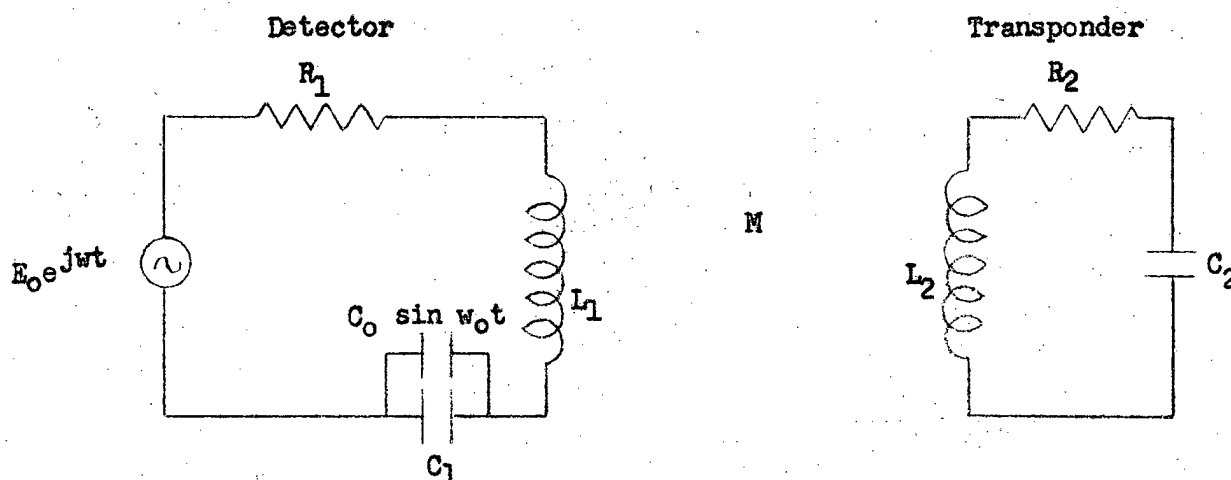


Figure 17. Detection System with Modulation of the Receiver Circuit.

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The oscillator is represented as a generator whose voltage is written as $E_0 e^{j\omega t}$ where E_0 is the crest voltage and ω is the angular frequency. The receiver circuit of the detector is indicated by L_1 and R_1 , the inductance and resistance of the detector coil, C_1 the main tuning capacitor which is ganged to a capacitor in the oscillator, and $C_0 \sin \omega_0 t$ the rotating capacitor where C_0 is the maximum value of capacitance and ω_0 is the angular frequency of capacitance variation. The transponder is represented by L_2 the inductance of the coil, R_2 the resistance of the coil and C_2 the tuning capacitor of the transponder. M is the mutual inductance between the transponder coil and the detector coil.

Writing the voltages for the detector loop

$$L_1 \frac{di_1}{dt} + R_1 i_1 + \frac{q_1}{C_1 + C_0 \sin \omega_0 t} = -M \frac{di_2}{dt} + E_0 e^{j\omega t}$$

and for the transponder loop

$$L_2 \frac{di_2}{dt} + R_2 i_2 + \frac{q_2}{C_2} = -M \frac{di_1}{dt}$$

are obtained where i_1 , i_2 , q_1 , and q_2 are the currents and charges respectively for detector loop and transponder loop. This is rewritten using the relation

$$i = \frac{dq}{dt} \text{ giving}$$

$$L_1 \frac{d^2 q_1}{dt^2} + R_1 \frac{dq_1}{dt} + \frac{q_1}{C_1 + C_0 \sin \omega_0 t} + M \frac{d^2 q_2}{dt^2} = E_0 e^{j\omega t}$$

and

$$L_2 \frac{d^2 q_2}{dt^2} + R_2 \frac{dq_2}{dt} + \frac{q_2}{C_2} + M \frac{d^2 q_1}{dt^2} = 0.$$

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Now

$$\frac{q_1}{C_1 + C_0 \sin w_0 t} = \frac{q_1}{C_1 (1 + \frac{C_0}{C_1} \sin w_0 t)} \approx \frac{q_1}{C_1} (1 - \frac{C_0}{C_1} \sin w_0 t)$$

using the binomial expansion and keeping only first order terms since $\frac{C_0}{C_1} \ll 1$.

This leads to a set of equations whose solutions are not always periodic¹. A qualitative explanation of this result can be obtained from consideration of the fact that the rotating capacitor will not be passing through resonance at the same phase of the oscillator signal each time. This condition is aggravated by the lack of constancy of angular speed of the rotating capacitor.

The second method of modulation (where the oscillator is frequency modulated) is indicated by Figure 18.

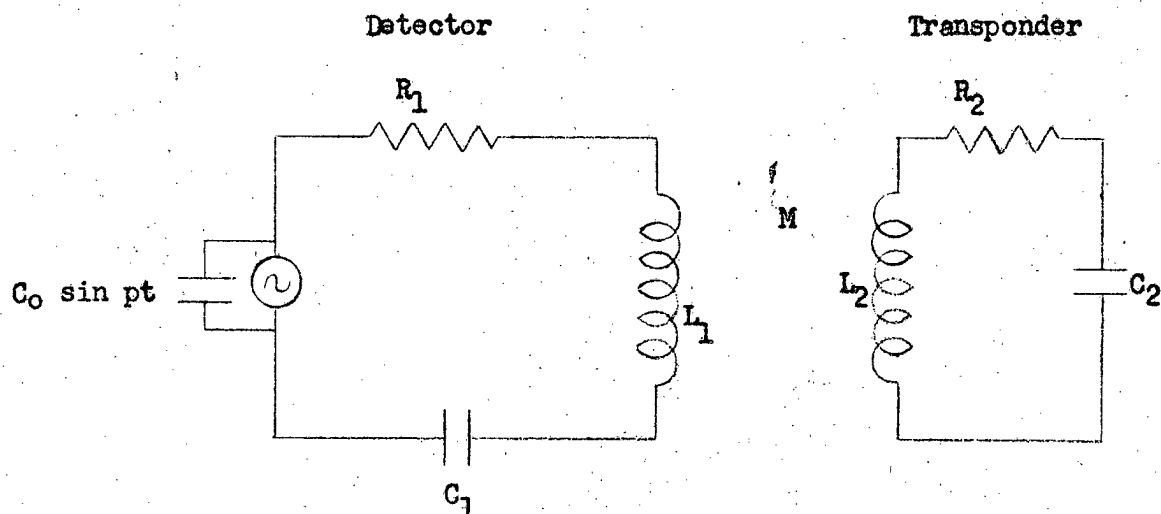


Figure 18. Detection System with Frequency Modulation of Oscillator.

¹ See Edson, W. A., Vacuum Tube Oscillators, (John Wiley & Sons Inc., New York, 1953), p. 355.

where

$$m_f = \frac{\text{variation of oscillator frequency from the mean frequency.}}{\text{modulating frequency}}$$
$$E_0 \left\{ J_0(m_f) \sin \omega t \right. \\ + J_1(m_f) [\sin (\omega+p)t - \sin (\omega-p)t] \\ + J_2(m_f) [\sin (\omega+2p)t + \sin (\omega-2p)t] \\ + J_3(m_f) [\sin (\omega+3p)t - \sin (\omega-3p)t] \\ + \dots \left. \right\}$$

Thus for angular frequency ω

$$i_1 = \frac{E_o J_o (m_f)}{R_1 + j (\omega L_1 - \frac{1}{\omega C_1}) + \frac{M^2 \omega^2}{R_2 + j (\omega L_2 - \frac{1}{\omega C_2})}}$$

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and for the other frequencies we add the terms

$$E_o \sum_{n=1}^{\infty} \frac{J_n(m_f)}{R_1 + j \left[(w+np)L_1 - \frac{1}{(w+np)C_1} \right] + \frac{M^2(w+np)^2}{R_2 + j \left[(w+np)L_2 - \frac{1}{(w+np)C_2} \right]}}$$

$$+ E_o \sum_{n=1}^{\infty} \frac{(-1)^n J_n(m_f)}{R_1 + j \left[(w-np)L_1 - \frac{1}{(w-np)C_1} \right] + \frac{M^2(w-np)^2}{R_2 + j \left[(w-np)L_2 - \frac{1}{(w-np)C_2} \right]}}$$

If p is made sufficiently small and m_f is sufficiently large, the errors due to tracking will be compensated for. The value of p determines the frequency between the discrete side bands and m_f determines the amplitudes of the side bands. Large values of m_f give a large number of side bands. If the frequency difference between the oscillator and the receiver circuit is less than $m_f p$, the current i_1 will behave almost the same as if the frequency difference was always zero. This is because of the contributions due to a number of side bands that are near resonance.

The second method of modulation where the oscillator is frequency modulated has two distinct advantages over the first method of modulation where the resonant frequency of the receiver circuit is varied. The first advantage is a less noisy signal. This is due to the fact that frequency modulation of the oscillator always produces a periodic signal. The second advantage is that the Q of the rotating capacitor is not critical when placed in the oscillator circuit. It need not be a very high Q capacitor. This allows the use of material which has better mechanical properties.